Comparison of Southern and Northern Annular Modes in MLS Products and Analyses

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Introduction

Annular modes couple winter high-latitude dynamics from the upper troposphere into the mesosphere, and the evolution of these modes during events such as sudden warmings and vortex recoveries has been an area of active research. In this work southern and northern winter MLS GPH modes (SAM and NAM) are compared with GPH from two operational DAS, ECMWF and GMAO GEOS-5, from two research assimilation products with higher model tops and more realistic gravity-wave parametrizations, CMAM and NOGAPS-Alpha, and from SABER measurements. Particular attention is given to the degree to which the different assimilations are able to capture the structure seen in the MLS observations, and to differences between the structure and evolution of SAM and the more-thoroughly-studied NAM. Of particular interest is the impact of the higher model tops (>0.001hPa vs 0.01hPa) and more-sophisticated gravity-wave (GW) representation in CMAM and NOGAPS-ALPHA.

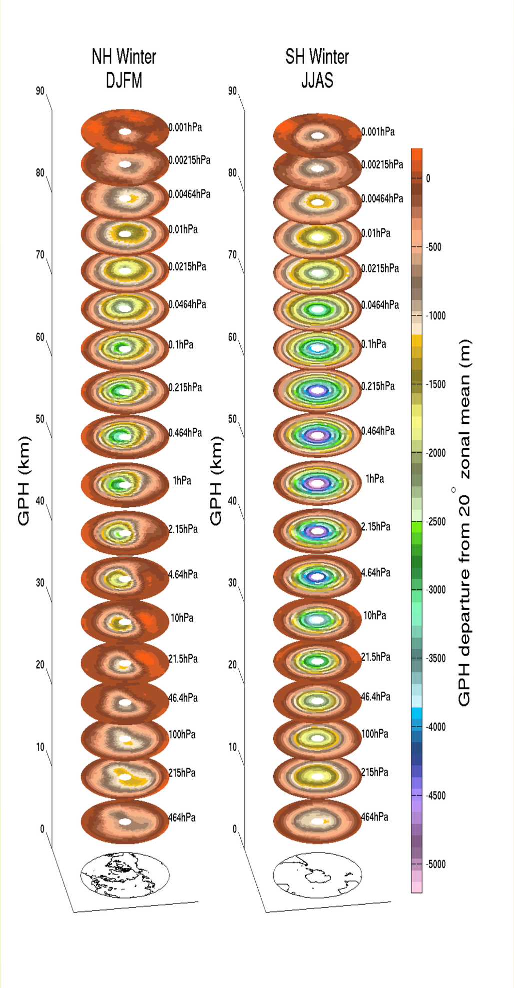


Figure 1 MLS Mean Winter GPH

•Mean GPH on pressure surfaces is calculated separately for the NH (DJFM) and the SH (JJAS) for each product or analysis (MLS GPH shown). EOF analysis is done on variability about these mean fields.

•Layer disks are plotted at the zonal mean GPH of their (20N or 20S) outer edges and this edge value is subtracted from the colors to show spatial variability over the hemisphere.

• The SH winter polar vortex is stronger and more axially symmetric than that of the NH, especially in the upper troposphere and stratosphere.

•MLS does not make measurements poleward of 82° due to its slightly non-polar sun-synchronous orbit.

•The pressure levels shown are a subset of the MLS retrieval levels. The bottom layer shown (464 hPa) is dominated by the GEOS-5 a priori, and 316 hPa is the lowest level recommended for scientific use.

Analysis Method

•Data are averaged in 8º longitude x 4º latitude x 5 day x MLS pressure levels (12 levels per decade of pressure in the UTLS up to 22hPa, 6 per decade to 0.02hPa, 3-per-decade above.)

•The mean at each lat-lon grid point is subtracted and covariance analysis is done, separately for the Northern Hemisphere winter (NH: DJFM poleward of 20) and for the Southern Hemisphere winter (SH: JJAS poleward of 20S).

•In the covariance matrix calculation, grid points are weighted by the square root of their area, under the assumption that high-latitude (small) grid boxes are highly-correlated with their neighbors.

•Empirical orthogonal functions (EOFs) are the eigenvectors of the covariance matrix.

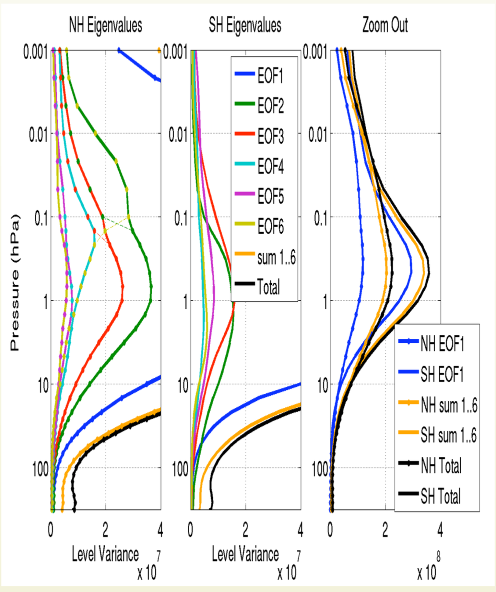


Figure 2. The largest six MLS winter GPH eigenvalues at each pressure level are shown for the NH (left) and SH (center), along with their sum and the total variance for the level. The right panel is a rescaled view showing only EOF1 and the sums for both hemispheres. Modes have been re-ordered at some levels in an attempt to follow geophysical modes vertically. In both hemispheres, the first six EOFs capture more than 90% of the total variability from the lower stratosphere through the mesosphere. In both hemispheres, winter GPH variance peaks at ~0.4 hPa, and while the total variance at the peak is ~60% higher in the SH, modes 2—6 are larger contributors in the NH.

EOF Analysis

•At each pressure level, the eigenvectors of the covariance matrix (EOFs) are orthogonal modes of variability. Their eigenvalues (???) indicate how much of the variance each captures. EOFs with unique eigenvalues have no cross-correlation with any other mode and are orthogonal geophysical modes of the atmosphere. When two EOFs have the same eigenvalue, any linear combination of the two is itself an eigenvector and geophysical significance may get muddled.

•Our goal is to identify geophysical modes and to see how they propagate vertically. When modes at adjacent levels have similar eigenvalues, well-separated from other modes, and have similar EOFs (Figure 3), they may be assumed to be geophysically related. When following eigenvalues vertically, as in Figure 2, there is indication that geophysical modes cross one another, and some confirmation may be found by comparing continuity in the EOFs above and below the crossing (Figure3) and by comparing the continuity in the timeseries of EOF projections (Figures 5&6). When the eigenvalues are close to one another, the eigenvectors may coalesce and may not be in a one-to-one relation with geophysical modes. Here, "close" must be defined relative to the uncertainty in the determination of the eigenvalues. The appearance that eigenvalues cross may be confirmed by comparing the eigenvalue patterns above and below the crossing point. An attempt has been made to sort the eigenvalues in Figure 2 to vertically link related geophysical modes, rather than to number modes at each level in descending order of their eigenvalues.

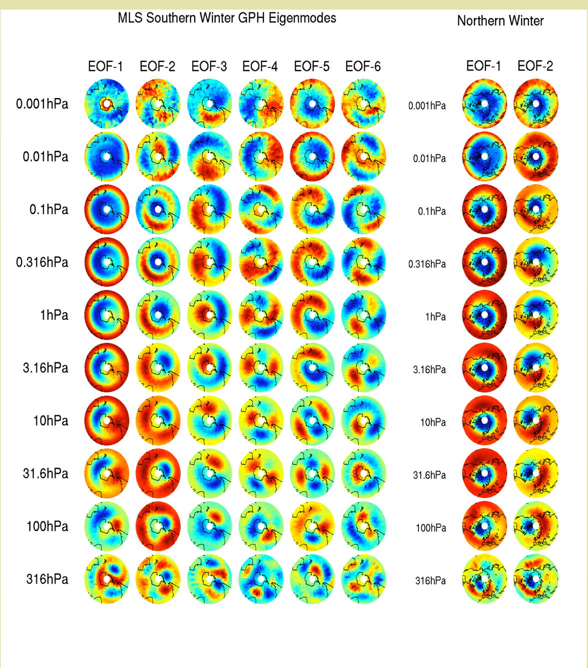


Figure 3. First six MLS SH winter GPH EOFs and first two NH EOFs. EOFs have been reordered at some levels, consistent with Figure 2, to associate common vertical structure.

MLS EOFs

•In the SH, the mean winter vortex is annular, but the leading EOF mode (i.e., strongest departure from that mean) is a shift of the vortex off of the pole (wave-1) from the upper troposphere through the upper stratosphere. This asymmetry is aligned with the orography of the Antarctic Peninsula and the tip of South America. The other leading modes are primarily mixtures of wave-1 and wave-2. These modes are in roughy descending order of eigenvalues, but have been exchanged at some levels in an attempt to make the vertical changes in the eigenvalues and EOFs smooth.

•In the NH, only the first two EOFs are shown. Here, the leading EOF is the well-known annularly symmetric NAM from 100 hPa—0.001hPa (Lee, et al., GRL 2009) capturing variations in vortex strength.

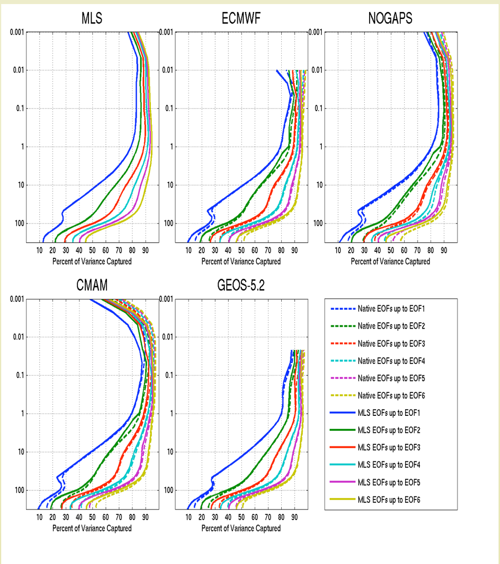
•In the NH lower stratosphere, modes 2-3 are wave-1-like and 3-4 are wave-2-like while in the upper stratosphere and mesosphere, modes 2-5 are a combination of wave-1 and an annular mode orthogonal to EOF-1 (with a different radial gradient). The yellow dots in Figure 2 attempt to follow a second annular mode through the column.

GPH Data Sets Compared:

Satellite Measurements from the **MLS** (Microwave Limb Sounder) on the Aura satellite (v2, 316-0.001hPa) and **SABER** (Sounding of the Atmosphere using Broadband Emission Radiometry; v1.7 on the TIMED satellite, 100-<0.001hPa).

The **GEOS-5.2** (model top 0.01hPa, Garcia & Boville (JAS 1994) non-orographic gravity wave drag, non-conservative implementation) and **ECMWF** (model top 0.01hPa, Rayleigh friction in lieu of non-orographic gravity wave scheme) operational assimilation systems.

The **CMAM-DAS** (model top ~0.0006hPa, Scinocca (JAS 2003) non-orographic gravity wave parameterization) and **NOGAPS-ALPHA** (model top ~0.0005hPa, Garcia, et al. (JGR 2007) non-orographic gravity wave drag, conservative implementation; assimilates MLS and SABER temperatures) research data assimilations systems.



• **Figure 4.** The cumulative fraction of variance of each of five data sets that is captured by the leading MLS EOFs (solid lines) and by "native" EOFs calculated from the covariance of each of the data sets (dashed lines). In the mid to upper stratosphere, MLS EOFs are nearly as good at capturing analyses' variance as are the native EOFs, while above 0.1 hPa and in the UTLS the variability of the analyses is not captured as well by the MLS EOFs. MLS and NOGAPS (which assimilates MLS) are very similar in the highest levels and have variance not present in CMAM. CMAM begins to diverge from MLS and NOGAPS at 0.1hPa (suggesting more variance in smaller-scale modes), and to lose organized structure above 0.005 hPa. GEOS-5 and ECMWF show significant differences from MLS above ~1hPa. Calculation of these quantities for SABER is problematic because of the TIMED satellite's yaw cycle.

Figures 5 and 6: Time-Series of Projections on MLS EOFs

•MLS EOFs provide a consistent basis in which to compare variability in different data sets. EOF1 and EOF2 projections are shown on different color scales, but they are common for the two hemispheres. SH EOF1 saturates in the final warmings, reflecting the dissipation of the deep mean vortex.

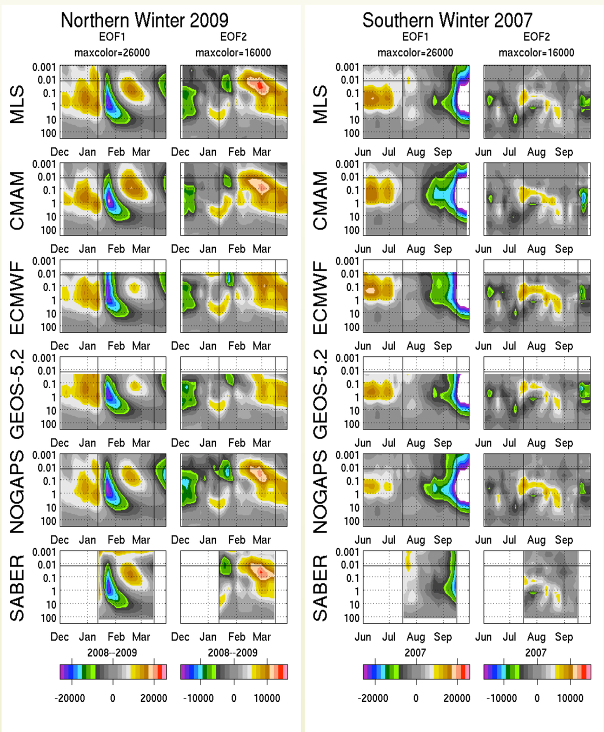
•To the extent that EOF1 is annular, positive EOF1 anomalies indicate a strengthening of the polar vortex with corresponding lowering of vortex temperatures and lowering of GPH on fixed pressure surfaces. Peak-to-peak amplitudes correspond to GPH anomalies as large as 5 km near 0.3hPa.

•CMAM and NOGAPS have qualitatively very similar stratospheric and mesospheric structure to that of MLS.

•GEOS-5.2 and ECMWF show significantly different patterns from MLS (and from each other) above ~1hPa, particularly during and after the 2009 SSW event.

• NOGAPS and MLS have a similar high EOF1 anomaly above 0.01hPa immediately before the SSW events in both 2006 and 2009.

•None of the analyses show as strong of a high EOF2 anomaly near 0.03hPa in the immediate recovery from the SSW events as is seen in MLS.



• **Figure 5.** Time-series projections of all data sets onto the first two MLS EOFs for NH winter, 2008-2009, and SH winter, 2007.

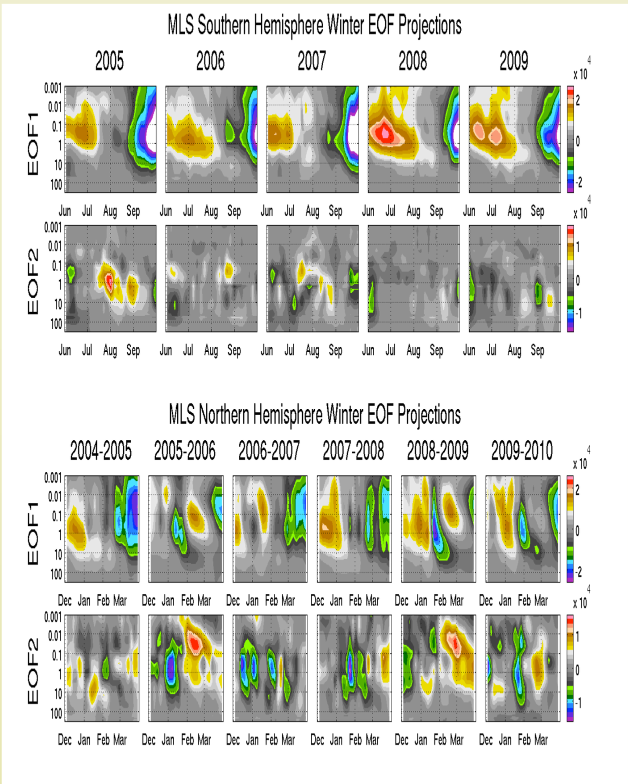


Figure 6. The time-series projections of MLS GPH variability onto its first two EOFs for all NH and SH winters, showing iinterhemispheric and interseasonal variability.

Summary

•EOF analysis of MLS GPH from the upper troposphere through the mesosphere highlights the vertical structure and coherence of leading patterns of wintertime variability in the northern and southern hemispheres.

•The leading EOF mode in the SH winter represents a shift of the vortex off the pole in the upper troposphere through upper stratosphere, in contrast to the annular pattern in the NH (NAM).

•CMAM successfully represents the variability seen in MLS GPH through the stratosphere and most of the mesosphere, without assimilation of data above the upper stratosphere.

•NOGAPS variability agrees very well with MLS through the mesosphere, reflecting a combination of adequate modeling of the middle atmosphere and the successful assimilation of high-altitude data.

•Representation of variability in the upper stratosphere and mesosphere in GEOS-5.2 and ECMWF is hampered by the models' low tops and crude NOGW representations.